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COLD DARK MATTER'S SMALL SCALE CRISIS GROWS UP

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ABSTRACT

The Cold Dark Matter (CDM) theory predicts a wealth of substructure within dark halos. These predictions match observations of galaxy clusters like the nearby Virgo cluster. However, CDM has a "small scale crisis" since galaxies dominate the halo with little substructure while the model predicts that galaxies should be scaled versions of galaxy clusters with abundant substructure. Compared to CDM predictions, the Milky Way and Andromeda are "missing" objects with velocity dispersions $\sigma \geq 10$ km s^{-1}. The energy scale of these missing satellites is low enough that stellar winds and supernovae might remove gas and suppress the formation of their luminous stellar components. Here, we show that the small scale crisis persists in fossil groups that have masses of up to 40% of the nearby Virgo cluster of galaxies. Fossil groups are missing satellites with luminosities that occur at the predicted frequency in the Virgo cluster. Moreover, the "missing galaxies" in fossil groups are nearly as luminous as the Milky Way with a velocity dispersion $\sigma \leq 150$ km s^{-1}.

Subject headings: cosmology: observations – cosmology: – dark matter – galaxies: clusters: general – galaxies: formation

1. INTRODUCTION

The formation of structure in the universe by the hierarchical clustering is an elegant and well-defined theory that explains observations of the universe on large scales (Blumenthal et al. 1984). In early simulations, it seemed that merging was too efficient to be consistent with the observed hierarchy of structures (White & Rees 1978). This *"overmerging"* problem was reproduced in simulations for several years (White et al. 1987, Frenk et al. 1988). While overmerging was a virtue on the scale of galaxies, it was a problem for rich clusters of galaxies. Solutions focused on the role of gas dynamics in making lumps within rich clusters of galaxies (Katz & White 1993). Eventually, Moore, Katz and Lake (1996) showed that numerical heating dominated over physical mechanisms unless simulations had nearly 10^6 particles within the virial radius of a cluster. Simulations with this resolution reversed the picture, overmerging disappeared and halos the size of the Milky Way are predicted to have nearly the same scaled distribution of substructure as the Virgo cluster (Moore et al. 1999, hereafter M99; Klypin et al 1999).

This strong prediction can be tested observationally. A Milky Way sized halo should have ∼500 satellites within 500 kpc, with circular velocities greater than 5% of the parent halo's velocity, *i.e.* $V_{cir}/V_{parent} > 0.05$, in contrast to a scant 11 that are observed (Klypin et al. 1999; M99).

It has been suggested that the stellar components of the Milky Way satellites might have accumulated in the core regions of their dark halos where the characteristic velocities σ are smaller than the asymptotic value of V_{cir}. The observed velocities of Milky Way's satellites would be re-mapped to much higher peak values than expected, shifting the objects plotted in Fig.1 (left panel) to the right until they match the theoretical prediction (Hayashi et al. 2003). There are still many satellites missing at lower peak velocities compared to CDM predictions, but these are declared to have gone dark owing to the ejection of gas from systems with low escape velocities of only 20 - 60 km s^{-1}. These objects are also deficient in the field (*c.f.* Kauffmann, White & Guiderdoni 1993) where the same processes could keep them from being observed.

Is this the solution to the overmerging crisis? The ROSAT X-ray satellite discovered a new class of objects: fossil groups (Ponman et al. 1994). RXJ1340.6+4018 at redshift 0.171 is the archetype with a bright isolated elliptical galaxy $M_R = -22.7$, surrounded by dark matter and a hot gaseous halo. The spatial extent of the X-ray emission, ∼ 500 kpc, the total mass, $\sim 6 \cdot 10^{13}$ M$_\odot$, and the mass of the hot gas correspond to a galaxy cluster ∼ 40% as massive as Virgo, and the optical luminosity of the central galaxy is comparable to that of cluster cD galaxies (Jones, Ponman & Forbes 2000, hereafter JPF00). Five additional fossil groups have been confirmed spectroscopically. For one of them, RXJ1416.4 the X-rays temperature is estimated to be ∼ 1.5 keV (Jones et al. 2003). Fossil groups are not rare. Their number density is $\sim 2.4 \cdot 10^{-7}$ h_{50}^3 Mpc^{-3} using the definition that they have a dominating giant elliptical galaxy with the next brightest object being 2 magnitudes fainter, embedded in a X-ray halo with a luminosity 10-60 % of the Virgo cluster (Vikhlinin

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et al. 1999; Jones et al. 2003). They comprise ∼20% of all clusters and groups with an X-ray luminosity larger than $2.5 \cdot 10^{42} h_{50}^{-2}$ ergs^{-1}, and host nearly all field galaxies brighter than $M_R = -22.5$ (Vikhlinin et al 1999). Their total mass density is comparable to massive galaxy clusters. Their high mass-to-light ratio, $M/L_R \sim 300$, is comparable to Virgo. The luminosity-temperature relations are also similar (Jones et al. 2003).

We define *overmerged* systems as objects dominated by a single central object with weak substructure with the Milky Way as a local prototype. In contrast, *clusters of galaxies* have abundant substructure and a central galaxy with a velocity dispersion that is considerably less than the overall dark halo, the local prototype being the Virgo cluster. In this Letter, we examine overmerging in systems with masses intermediate between the Milky Way and the Virgo cluster.

2. THE CUMULATIVE SUBSTRUCTURE FUNCTION IN FOSSIL GROUPS

We compare the cosmological model predictions (De Lucia et al. 2004) to the substructure function of RXJ1340.6+4018, Virgo and Coma clusters of galaxies, Hickson Compact Groups (HCGs) and the Local Group. In Fig.1 the cumulative substructure function is the number of objects with velocities greater than a fraction of the parent halo's velocity.

For the groups and clusters, we convert luminosity functions (LFs) to substructure functions using using the Tully-Fisher relation for the spirals (Tully & Pierce 2000) and the Faber-Jackson (1976) relation for early-type galaxies. RXJ1340.6+4018 has a velocity dispersion of $\sigma_{parent} \sim 380$ km s^{-1} ($V_{parent} = \sqrt{2}\sigma_{parent}$) and its brightest galaxy has $\sigma \sim 260$ km s^{-1} (JPF00). The substructure plots skip the largest central galaxy. With the observations, it can be difficult to disentangle the central object from diffuse light in the cluster. However, a greater uncertainty comes from the simulations that might still have too little resolution in the very center of the cluster (Taylor, Silk and Babul 2003). For the second brightest object, we find $V_{cir}/V_{parent} \sim 0.35$ and proceed down the LF to construct a substructure function. For the Virgo cluster, we use the LF of Binggeli, Sandage & Tammann (1985) and for the Coma cluster the LF of Trentham (1998).

The cumulative distribution of satellites in the Milky Way's halo and Andromeda's halo are also plotted. Here, the measured one-dimensional velocity dispersions of satellites (Mateo 1998) are converted to circular velocities assuming an isotropic velocity dispersion (M99).

We would like to have a sample of LFs for objects with intermediate mass between the Local Group and Virgo cluster. There are only a few LFs known in this range, most of them from studies of Hickson (1982) compact groups. Hunsberger, Charlton & Zaritsky (1998) constructed an LF from 39 compact groups. To convert this to the substructure function in Fig.1 (right panel), we adopt $\sigma \sim 370$ km s^{-1} for the typical velocity of the parent's halo and use the Tully-Fisher relation that Mendes de Oliveira et al. (2003) have shown applies to galaxies in HCGs.

In the right panel of Fig.1, we show a composite substructure function for the 5 loose groups in Zabludoff & Mulchaey (2000). These look very different than the other substructure functions, appearing to be shifted strongly to the right compared to the composite for the 39 HCGs. While these objects could be very different, loose groups are likely to have even more contamination than typical HCGs (Hernquist, Katz and Weinberg 1995). Zabludoff & Mulchaey (2000) point to the Local Group as an archetype of loose groups. While the Local Group is certainly a physical association, it is not bound and virialized. If we treated it as a group, the Milky Way would appear as the second brightest member and the rest of the points would move upward by a factor of 2. This would indeed be an archetypal substructure function for a loose group. If instead, we wait for the virialization of the group and the merger of M31 and the Milky Way, we would see something extremely similar to the substructure function of the individual virialized systems. While the fist few points of the combined substructure function of the 39 HCGs place them high on the substructure function, the LFs quiclky flatten at the faint end and show a deficit of structure there (right panel Fig.1). The combined substructure function of the 5 loose groups from Zabludoff & Mulchaey (2000) show behavior that is intermediate between the HCGs and the brighter clusters.

Zabludoff & Mulchaey (1998b) find that their two groups with the greatest number of members (HCG 62 and NGC 741) can be broken into two distinct subgroups. They suspect that the fraction with such structure is much higher than 40% since their statistic is less sensitive for the groups with fewer members and requires an angular offset of the centroids of the subclumps.

In the left panel of Fig.1, the similarity of the substructure function in RXJ1340.6+4018 to the Milky Way and Andromeda is striking. It shows that fossil groups are also *overmerged* objects. However, for galaxies of any given V_{cir} that are missing in the fossil group, galaxies with the same V_{cir} appear with the predicted frequency in Virgo and are observed in the field as well. The Virgo cluster contains six L* galaxies (Binggeli, Sandage & Tammann 1985) with L* being a characteristic luminosity in the luminosity function and is roughly the luminosity of the Milky Way. Fossil groups show one or no L* galaxies (Mulchaey & Zabludoff 1999; Jones et al. 2003), while the CDM substructure function would predict a few in each group. The likelihood that the substructure in fossil groups and in the Virgo cluster is drawn from the same, universal cosmological distribution function is negligibly small, especially at the low mass end.

3. THE TRANSITION FROM OVERMERGING TO GALAXY CLUSTERS

Where does the transition from *overmerged* systems to galaxy clusters with substantial substructure occur? Is the transition from overmerging to clusters smooth, abrupt or merely ill determined with a scattering of points?

Studies of Hickson (1982) Compact Groups, loose groups (Zabludoff & Mulchaey 1998a,b), the 2dF Galaxy Redshift Survey (2dFGRS; Colless et al. 2001), the Sloan Digital Sky Survey (SDSS; York et al. 2000) are sources for catalogs of groups and clusters. Balogh et al. (2003) analyzed both surveys to look at "galaxy ecology" or star formation as a function of environment. Desai et al. (2003)

fit some circular velocity functions to a sample from the SDSS and compared this to the large simulation by Reed et al. (2003). The critical range of group velocity dispersions is $250-400$ km s^{-1}, as this is where one would like to see the transition from overmerging on the scale of galaxies to the abundant substructure in clusters. In this range, there are 39 objects in the HCG sample of (Hunsberger, Charlton & Zaritsky 1998), 5 loose groups in the sample of Zabludoff & Mulchaey (1998a), 9 SDSS groups from Desai et al. (2003) and roughly 40 groups from the 2dFGRS (Balogh et al. 2003). Only the HCGs and the loose groups have LFs that are deep enough to be used in the bottom panel of Fig.2. There are a few other sources with not quite enough information to be used. For example, the LFs observed by Muriel, Valotto & Lambas (1998) shows a number of groups with LFs that are similar to the HCG sample of Hunsberger, Charlton & Zaritsky 1998, but the typical velocity dispersions for the groups is unknown.

We plot the number of galaxies brighter than $M_B < -19$ versus velocity dispersion in the top panel of Fig. 2 using the data from Balogh et al. (2003) and Desai et al. (2003). As expected, the number of galaxies increases with the velocity dispersion of the group. We added a line that shows what one would observe if the substructure function of Virgo were universal. At low dispersion, it appears that objects have more substructure than scaling Virgo. This owes to the criteria that there must be 10 members to be included as a group in the samples. With the cut of $M_B < -19$, the Milky Way would still be consistent with a scaled Virgo substructure function. At the high velocity dispersion end, there is less substructure than the scaled Virgo substructure function predicts. This is consistent with previous studies where the luminosity function within large clusters was relatively constant rather than scaling with cluster size (De Propis et al. 2003). There is not a large sample of such clusters in CDM simulations. There are a few high resolution runs of individual clusters (Borgani et al. 2002) and the high resolution run of Reed et al. (2003) simulated a volume of 100 Mpc side which is not large enough for a good sample of large clusters.

There are fewer mass functions that reach $V_{cir}/V_{parent} > 0.05$ and these have been collected in the bottom panel of Fig. 2. This sample includes all the systems shown in Fig. 1 and adds the Fornax cluster. Fornax has a velocity dispersion $\sigma \sim 374$ km s^{-1}, comparable to the RXJ1340.6, but has little diffuse X-ray emission (e.g. Horner, Mushotzky & Scharf 1999) and considerably more substructure (obtained from the luminosity function of Ferguson & Sandage 1989), albeit less than a scaled version of Virgo would predict. For RXJ1340.6+4018, integrating the luminosity function within the large error bars gives an upper limit of ~ 30 members with $V_{cir}/V_{parent} > 0.05$, but only nine are spectroscopically confirmed. We use 9 as the number of substructures and show the current uncertainty with an error bar to 30 in Fig.2.

The loose groups might not be a single bound systems but projections of filaments of galaxies (Hernquist, Katz & Weinberg 1995) or superposition of multiple structures (Zabludoff & Mulchaey 1998b). At the moment, the loose groups are the main objects that we have have in the transition region intermediate between overmerged systems and clusters. Fig.2 is sparsely populated, but argues for substantial variation of properties of systems with velocity dispersions of $300-400$ km s^{-1}.

4. DISCUSSION

What is the origin of the fossil groups? The similarity in their cumulative galaxy distribution with the Local Group (Fig. 1, left panel) suggests that they are the end result of merging of L* galaxies in low density environments (Jones et al. 2003). The giant elliptical in RXJ1340.6+4018 has no spectral features which would indicate recent star formation. Hence, the last major merger must have occurred several gigayears ago (JPF00).

Although the substructure function of fossil groups and the Local Group are similar, the merger of the Milky Way and the Andromeda galaxy will not form an X-ray dominated fossil group. The mass of the merged Local Group will be $\approx 3-5\cdot 10^{12}$M$_\odot$ (Kahn & Woltjer 1959) within 300 kpc with $V_{max} \approx 290$ km s^{-1}, 10% higher than Andromeda and significantly less than observed fossil groups. Merging won't change the circular velocity of the satellites, though they will change morphology and than will fade. The result will look more like Centaurus A which has a substructure function like the Local Group with an elliptical at the middle but no X-ray emission and a total mass that is less than fossil groups (Karachentsev et al. 2002). Additional "two by two" hierarchical mergering would make a system that matched the optical properties of a fossil group, but it is not clear why "overmerging" would propagate up the hierarchy to produce fossil groups while clusters like Virgo have galaxies of the same luminosity as those that are missing in fossil groups.

X-ray halos in fossil groups and clusters are an outstanding problem (Mulchaey 2000). In general, it is difficult to keep all the gas from cooling at early times and becoming a part of the galaxies. Since Virgo has extensive X-ray emission while Fornax has a paltry intracluster medium, we have all 4 combinations of systems that are overmerged or having abundant substructure together with those with abundant or very little intracluster medium. It might well be that having fossil groups among the progenitors of a cluster is key to producing their X-ray emission.

Dynamical friction and merging aren't a general solution to the overmerging problem. Clearly, these dynamical effects were included in the full numerical simulations that first highlighted the problem in the CDM model. Any specific substructure function evolves in the same way by dynamical friction and merging independent of the parent mass. The dynamical friction timescale t_{df} is proportional to the crossing time of a system t_{cr} divided by the fractional mass of the sinking object (e.g. $t_{df} \sim 0.05\ t_{cr}/(M_{sinker}/M_{parent})$. The crossing time of all virialized halos is the same. Further the fractional mass of the sinking satellite is a function of the variable V_{cir}/V_{parent} in the substructure function and the tidal radius of the satellite which is determined by it's orbital pericenter as fraction of the virial radius r_{peri}/r_{virial}. All of these quantities scale with parent mass such that the evolution of the substructure function is independent of the mass of the parent halo. Dynamical friction can be important in promoting the merger of the largest objects in less than one Hubble time, within a parent halo, but dynamical friction alone will not create substructure func-

tions that are different for different parent masses. Of course, galaxies could have had a long time to evolve by dynamical friction, but this will not affect the substructure function below V_{circ}/V_{parent} of 0.2.

What mechanisms could explain the substructure function of fossil groups? The first thought might be merely cosmic variance. The top panel of Fig. 2 shows the variance in the groups selected from the SDSS (Desai et al. 2003). The figures in Desai et al. (2003) show that the variance seen in the groups selected from the SDSS (shown here in Fig. 2) is already 2-3 times greater than observed in the simulation of a $(100\mathrm{Mpc})^3$ volume simulated by Reed et al. (2003). The fossil groups lie well outside of the variation seen in the large simulation, but they are rare enough that a larger volume is required to be definitive.

One might extend the proposal of Hayashi et al. (2003) who argue for shifting points to the right and then blowing the baryons out of the smallest objects. While gas ejection is attractive to explain the missing satellites of the Local Group, it would take nearly 10 times as much energy to blow the gas out of the missing galaxies in fossil groups. Further, the gas ejection must also be tuned to the environment since the same galaxies appear at the predicted frequency in clusters and the field. We have no evidence that L* galaxies are fragile in either of these environments. The same tuning argument is a severe constraint on solutions that alter the initial cosmic fluctuation spectrum. Star formation could be suppressed at a higher energy scale in fossil groups by appealing to intense bursts of star formation as seen in starburst galaxies at high redshift or by appealing to the power of a super-massive black-hole. The comoving number densities of the ULIRG starburst galaxies at high redshift roughly matches the number densities of the halos predicted at the same redshift by hierarchical merging leading to the speculation that there is a starburst galaxy in every halo with mass $\sim 10^{13} M_{\odot}$ (Somerville, Primack & Faber 2001). These halos will also be the progenitors of objects the size of fossil groups and larger.

Such an energy injection could also create the reservoir of gas needed for large clusters as well as the observed entropy floor in that gas. As substructure is suppressed, gas falling into the deep potential well of a massive dark cluster will be more effectively heated in an accretion shock. This could enhance substructure suppression and boost the fraction of baryons that settle into a single luminous galaxy. However, the presence of intracluster gas doesn't appear to be related to the substructure function as we see all combinations of X-ray emission and substructure functions in our small sample of systems. It's also not clear why energy input was so effective at suppressing substructure in a fossil group, but so ineffective in Fornax and Virgo which have the powerful sources Fornax A and M87.

Fossil groups offer a better environment to test these hypotheses than galaxies that are counterparts to the Milky Way. If the galaxies have been altered in fossil groups, they need to be a factor of ten fainter than expected from their dark matter mass. As a result, they should have velocity dispersions that are anomalously high by nearly a factor of two.

Gravitational lensing provides three possible tests. M99 suggested direct detection of mass clumps using the brightness ratio of lensed images. With this technique, Dalal and Kochanek (2002) used a sample of isolated ellipticals that are likely the centers of fossil groups. They find that a few percent of the mass in halos is in clumps with masses in the range of $10^6 - 10^9 \mathrm{M}_{\odot}$ which is a factor of a few below what is seen in simulations (M99; Klypin et al. 1999; Ghigna et al. 2000). However, Zentner and Bullock (2003) found that Dalal and Kochanek's model underestimated the substructure since they placed substructures uniformly in the halo rather than allowing for stripping and destruction in the central regions where they had the greatest sensitivity. There are other consequences associated with lumps that are more massive than 10^9 $\mathrm{M}_{\odot}$. In the strong lensing case, the positions of images will shift betraying individual lumps rather than just their statistical properties. This was not seen by Dalal and Kochanek (2002). Shifts in the center of mass may also be seen with weak lensing maps. Here, one would compare the centers defined by the brightest galaxy, the X-ray emission and the lensing map. If there is significant clumping, the brightest galaxy will be displaced from the center of mass defined by the other two. The center of the X-ray emission generally agrees with the location of the brightest galaxy (Mulchaey 2000), but the lensing map should be a more sensitive test.

5. CONCLUSIONS

Gas processes have been invoked to explain the absence of the dwarf satellites in the Milky Way and the field compared to CDM predictions. However, we now find that overmerging persists to the larger mass scale of fossil groups where galaxies as massive as the Milky Way and the Large Magellanic Cloud are "missing", though they appear at the predicted abundance in both the field and clusters of galaxies. Fig.2 shows that the "overmerging" behavior is more dependant on the mass of the parent halo rather than the mass of the satellite, though this could owe to our limited sample size. We have pointed to some key observations that can resolve whether this owes to energetic phenomena or is a result of an unknown source that is closely tied to the mass scale of the parent halo. To resolve this issue, we need more systems with velocity dispersions in the range of 300-400 km s^{-1}. For the present data, *overmerging* behaviour seems to be the generic behaviour for objects with T$\leq$ 1 keV .

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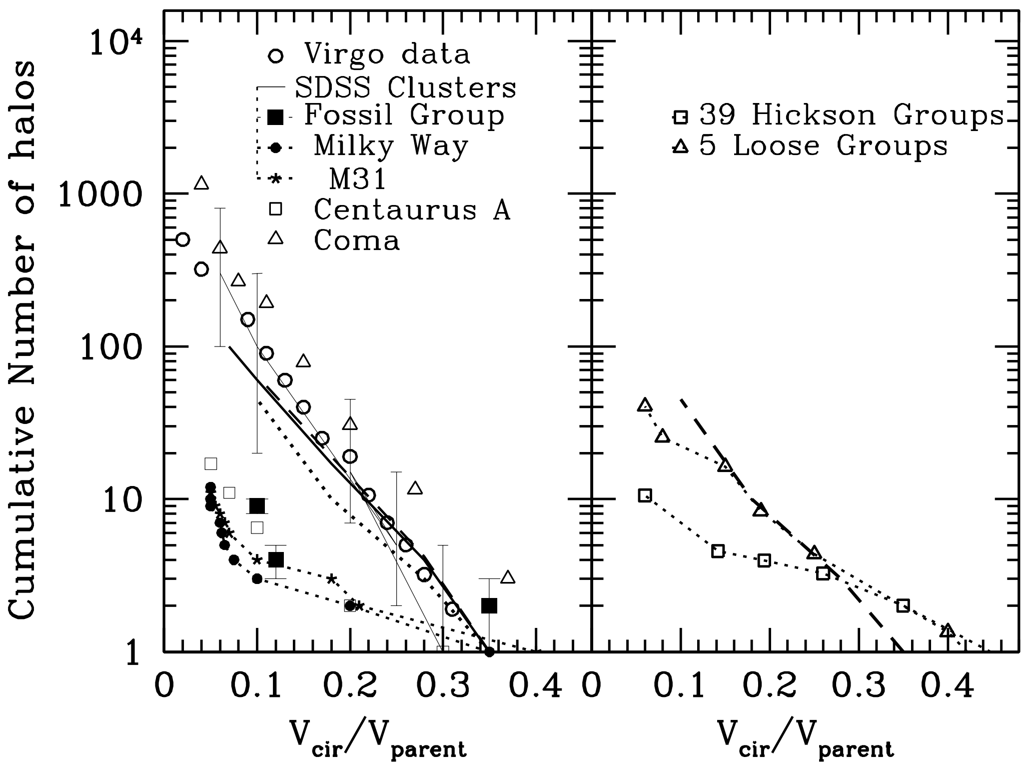

FIG. 1.— The observed cumulative substructure function of galaxies within RXJ1340.6+4018 (fossil group), Virgo and Coma clusters of galaxies, clusters from SDSS, the Local Group and Centaurus A compared to CDM predictions (De Lucia et al. 2004) (left panel). The thick solid line is the CDM prediction for a halo of $10^{15}\ h^{-1}\ M_{\odot}$, the dashed line and dotted lines for halos of $10^{14}\ h^{-1}\ M_{\odot}$ and $10^{13}\ h^{-1}\ M_{\odot}$, respectively. The substructure function is the number of objects with velocities greater than a fraction of the parent halo's velocity. The right panel shows a sample of 5 loose groups from Zabludoff & Mulchaey (1998a) and the function derived from the LF of 39 Hickson compact groups (Hunsberger, Charlton & Zaritsky 1998) compared to CDM predictions (dashed line).

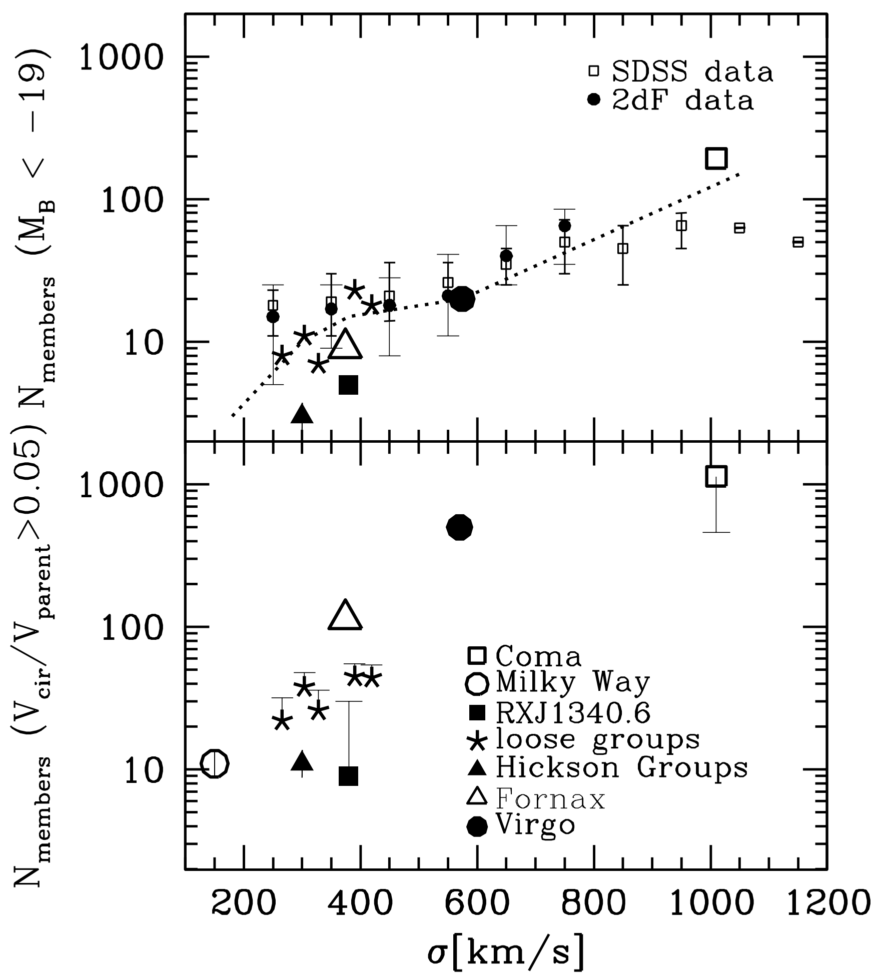

Fig. 2.— The top panel shows the number of members brighter than $M_B < -19$ versus the velocity dispersion for groups derived from the 2dFGRS (Balogh et al. 2003) and the SDSS (Desai et al. 2003). The systems in Fig. 1 are also included. Note that there are nearly as many systems in the point labeled "39 HCGs" as there are groups between 250 and 400 km s^{-1} in the 2dFGRS and SDSS samples. The dotted line shows what would be expected if the substructure function for Virgo was universal. The bottom panel shows the cumulative number of substructures with circular velocities larger than 5% of the parent halo's circular velocity versus the dispersion of the parent group for the sample shown in Fig. 1. Data for the Coma cluster of galaxies are from Trentham (1998), but the error bar accounts results from Mobasher et al. (2003) inferred from a spectroscopic LF. There is an overall trend with considerable scatter in the region intermediate from galaxies to clusters.